



The field enhancement factor of sand-blasted electrodes

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Abstract: A sample of six sand-blasted electrodes has been subjected to both mechanical and electrical investigations. For this sample, the mean electric field enhancement factor is found to be 6.6.

Introduction

All practical conductor surfaces possess an inherent microscopic roughness, the dimensions of which are dependent on the production processes utilised, see [1]. This roughness leads to a perturbation of the macroscopic electric field such that, for the same macroscopic conductor geometry, the maximum field strength E_{\max} of the rough surface will be greater than the maximum field strength E_a of the corresponding smooth surface. This increase in field strength due to surface roughness can be quantified in terms of a field enhancement factor m , where m is defined as

$$m = E_{\max}/E_a \quad (1)$$

with $m \geq 1$. In general the m values associated with practical surfaces are unknown.

Recently, McAllister and Crichton proposed a method to determine the m value of a rough conductor surface [2]. Owing to the experimental procedure employed, this m value represents an effective value for the surface as a whole. In the present paper the method, which is based upon the detection of discharge onset in a gaseous medium at the surface in question, is used to investigate the scatter in m for a particular surface treatment.

When the surfaces of a series of conductors are mechanically treated, the resultant microscopic surface geometries will be similar, but not identical. As a consequence of this spread in the geometric characteristics of the roughened surfaces, the m values associated with nominally identical conductors will also exhibit a scatter. To determine this scatter for sand-blasting, a sample of six electrodes has been examined both electrically and mechanically. The mechanical study relates to the basic surface roughness parameters, R_a and R_t [3].

The results indicate that, as the electrodes were treated at different times during the lifetime of the sand, there arises a distinct variation in the recorded surface roughness parameters. However this variation does not manifest itself so clearly in relation to the electrically-determined field-enhancement factors, which lie in the range 4.8 - 8.5, with a mean value of 6.6.

Theoretical Aspects

The experimental method is based upon the determination of the surface roughness factor ξ for the surface in question. This dimensionless parameter expresses the reduction in the insulation strength of a compressed gas system from that predicted theoretically on the basis of the streamer criterion applied to the idealized macroscopic geometry [4]. Hence ξ can be expressed as

$$\xi = U_o/U_{ot} \quad (2)$$

where U_o is the actual discharge onset voltage while U_{ot} is the theoretically predicted value associated with the idealized (i.e. smooth) electrode. From the theory of discharge onset in a gaseous medium at a rough surface, it can be shown that, at high gas pressure, ξ tends to a limiting value, ξ_{lim} , and that this value is in fact equal to the reciprocal of the field enhancement factor [2], i.e.

$$\xi_{lim} = \frac{1}{m} \quad (3)$$

Although the value of ξ for a practical surface can only be determined experimentally, an appreciation of the variation of ξ with gas pressure p can be gained by considering simple models of a rough surface. A typical variation of ξ for SF_6 is shown in Fig.1 for a hemispherical protrusion of radius R . For such a protrusion $m = 3$ and from Fig.1 it is evident that as $pR \rightarrow \infty$, $\xi \rightarrow 1/3$.

With a knowledge of the test gap geometry and the electrical characteristics of the test gas, the calculation of U_{ot} is straightforward. Full details can be found in [2]. With respect to the determination of U_o , however, it is in practice only possible to perform experiments over a finite range of gas pressure, typically $0.1 \leq p/\text{MPa} < 1$. In these conditions it is necessary to undertake a regression analysis of the experimental data to obtain ξ_{lim} and thus the derived m value has an inherent uncertainty.

Experimental Measurements

Six circular cylindrical electrodes (radius 5 mm, length 450 mm) were sand-blasted by courtesy of Siemens AG (Berlin). These electrodes were treated at different times during the lifetime of the sand magazine, and thus the electrodes were numbered sequentially in the order in which these were received at our laboratory. Following receipt, each electrode was cleaned in an ultrason-

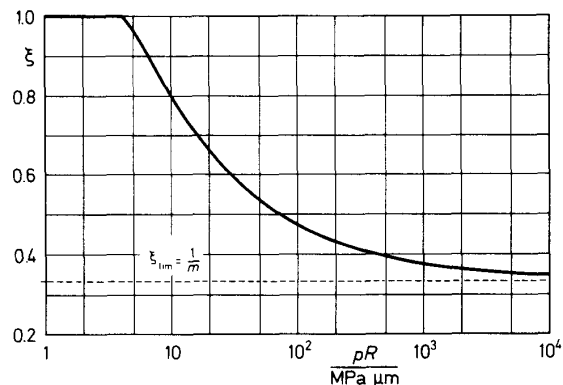


Fig.1. Surface roughness factor ξ for SF_6 .

ic bath, and thereafter stored in a protective envelope prior to use.

Mechanical Study

Measurements of the surface structure were undertaken using a high precision Perthometer, type WVR. The arm stylus had a tip radius of curvature of $3\text{ }\mu\text{m}$ and a tip angle of 90° . The output signal from the roughness meter was digitized and analysed subsequently to yield values for the surface parameters R_a and R_t ; see [3] for definitions. The measuring system was calibrated against a standard ($10\text{ }\mu\text{m}$ range) roughness specimen.

To sample the surface topography adequately, four 30-mm scans equally spaced around the electrode circumference were made on the centre section of each electrode. For the purposes of analysis, the 30-mm scans were sub-divided into 16 overlapping sections so that there was always the possibility of neighbouring peaks and troughs being taken together. For each electrode, the values of R_a and R_t derived for each of the 64 sub-scans were then treated statistically. The main data of this analysis are listed in Table 1.

As could be expected with sand-blasting, there is a scatter in the \bar{R}_a and \bar{R}_t values associated with the six bars. However, it is clear that bars 1 & 2 were not roughened to the same extent as the other four, see Table 1.

Electrical Study

The discharge measurements were undertaken with a coaxial cylinder gap over the pressure range 0.1 - 0.9 MPa using SF_6 as the test gas. The roughened inner electrode had a nominal radius of 5 mm while the gap spacing was 25 mm. The length of the constant diameter section of the outer electrode was 80 mm whereas that of the inner was 450 mm. The overall length of the flared, outer electrode was 160 mm. A coaxial test gap was selected as this geometry exhibits a large surface area associated with E_a .

Discharge onset (corona or direct-breakdown) was detected oscillographically for a negative DC applied voltage. No irradiation was used and the applied voltage was raised at $\sim 1\text{ kV/min}$. In the absence of direct breakdown at the higher gas pressures, discharge onset was

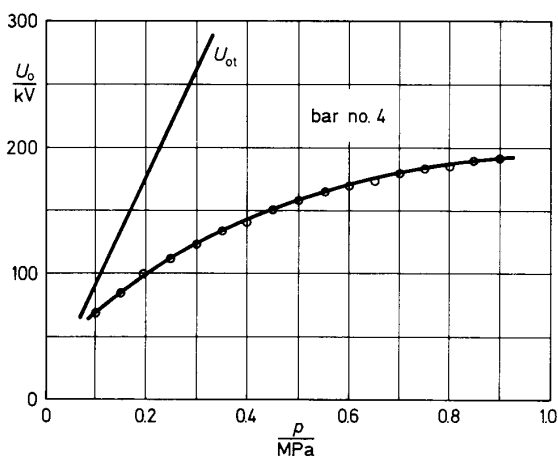


Fig.2. Discharge onset voltage U_o in SF_6 as a function of gas pressure p .

identified with the initial appearance of pre-breakdown current pulses, see [5,6].

A typical variation of the measured onset voltage with gas pressure is shown in Fig.2. To indicate the deleterious effect of surface roughness upon insulating strength, the calculated onset voltage characteristic for the idealized macroscopic geometry, U_{ot} , is included for comparison. This latter curve is derived assuming $\xi = 1$, see [4] for details. From (2) it is evident that, by combining the results in Fig.2, ξ can be determined.

As seen from Fig.2 however, the U_o measurements were performed at pressures exceeding 0.1 MPa and thus the non-ideal gas behaviour of SF_6 must be taken into account in the ξ evaluation. To do so we introduce the compressibility-corrected gas pressure p_z , with p_z defined as

$$p_z = p/Z(p,T) \quad (4)$$

where $Z(p,T)$ is the compressibility factor (≤ 1) for the gas and T the absolute gas temperature. In this study, the onset measurements were undertaken at room temperature which lay in the range $20^\circ\text{C} - 25^\circ\text{C}$. For any one set of measurements, the gas temperature fell by $\sim 1.5^\circ\text{C}$ during the course of the experiment. Further details of this aspect of the ξ evaluation can be found in [2]. The result of such an evaluation is shown in Fig.3, which now illustrates the variation of ξ with p_z .

Regression Analysis

On the basis of the fact that ξ tends asymptotically to a particular limiting value, see Fig.1, the regression analysis was based on an expression of the form

$$\xi(p_z) = \xi_{\text{lim}} + f(p_z) \quad (5)$$

with the function $f(p_z) \rightarrow 0$ monotonically as $p_z \rightarrow \infty$. For the present data, an exponential function was found to

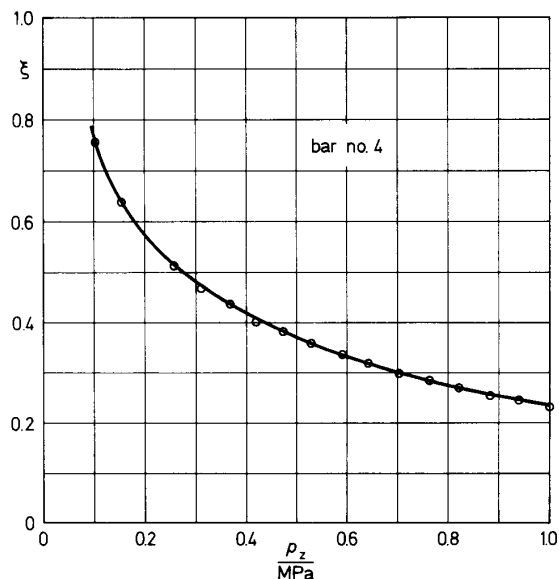


Fig.3. Variation of surface roughness factor ξ with compressibility-corrected gas pressure p_z .

be appropriate and hence the relationship used in the regression analysis was

$$\xi(p_z) = c + a \exp(bp_z) \quad (6)$$

where a and b are the regression coefficients and c is a constant.

A least-squares fitting technique was employed to determine a and b and the coefficient of determination r^2 was employed to assess the goodness-of-fit. In performing the analysis, the value of c was varied until r^2 displayed a maximum value, see Fig.4. The corresponding c value is then taken to be ξ_{lim} .

From Fig.4, it is evident that the c, r^2 curve shows a shallow maximum. This behaviour has been used to associate a measure of uncertainty in the determination of ξ_{lim} . For an r^2 effectively equal to $(r^2)_{max}$, i.e. agreement to three significant figures, the variation in c is on average 10%.

The values of m derived from the ξ_{lim} evaluation are listed in Table 1, from which the mean field enhancement factor \bar{m} is found to be 6.6, with a standard deviation $s(m)$ of 1.2. Thus the scatter in the m values is greater than the uncertainty in the ξ_{lim} determination. Although there is an increase in the R_a and R_t val- with sand 'aging', such a trend is less certain with respect to the corresponding m values.

Conclusion

With a sample of six electrodes, the field enhancement factors associated with a sand-blasting treatment have been found to lie in the range 4.8 - 8.5, with a mean value of 6.6. The mechanical surface parameters indicated a sand aging effect.

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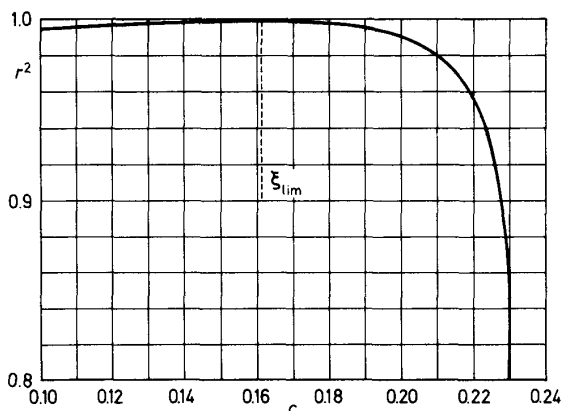


Fig.4. Variation of coefficient of determination r^2 with regression parameter c .

Table 1. Mean values of the surface parameters R_a and R_t for each bar together with the corresponding field enhancement factor.

bar no.	\bar{R}_t μm	s_t μm	\bar{R}_a μm	s_a μm	m	r^2
1	44.3	14.2	7.1	1.1	4.8	0.997
2	50.8	16.5	8.0	1.7	6.6	0.996
3	63.1	18.7	10.4	2.1	6.7	0.996
4	70.1	18.3	11.5	2.2	6.2	0.998
5	63.5	19.6	10.9	2.2	8.5	0.998
6	65.5	16.4	11.0	1.7	7.0	0.999

s_t and s_a are the standard deviations associated with \bar{R}_t and \bar{R}_a , respectively. $\bar{m} = 6.6$, $s(m) = 1.2$.

For roughness measurements, the cut-off was 2.5 mm.

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